

# Externally Mode-matched Cavity Quantum Electrodynamics with Charge-tunable Quantum Dots

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## Abstract

We present coherent reflection spectroscopy on a charge and DC Stark tunable quantum dot embedded in a high-quality and externally mode-matched microcavity. The addition of an exciton to a single-electron charged quantum dot forms a trion that interacts with the microcavity just below strong coupling regime of cavity quantum electrodynamics. Such an integrated, monolithic system is a crucial step towards the implementation of scalable hybrid quantum information schemes that are based on an efficient interaction between a single photon and a confined electron spin.

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Hybrid quantum information schemes combine the coherence properties and ease of manipulation of photons with the scalability and robustness of local quantum systems. Examples of local quantum systems include electron spins in quantum dots, defect centers in diamond, and trapped atoms or ions [1, 2]. Hybrid schemes such as quantum repeaters and quantum networks use the coupling between the local quantum system (qubit) and the optical field to reversibly map the quantum state of an injected photon onto the state of the local system [3, 4, 5, 6]. Other hybrid schemes use a joint measurement of emitted photons, which are entangled with their respective local qubit, to perform gate operations on the two spatially separated local systems [7, 8, 9, 10]. This latter scheme can be used to create entanglement between many local qubits as needed for cluster state quantum computation. Implementations based on trapped ions or atoms have reached operation fidelities greater than 80% for 2 remote qubit interactions. However, the overall success probabilities are currently limited to  $\approx 10^{-8}$ , due to the technical incompatibility of trapping the particles and coupling them efficiently to a single external optical mode [11, 12]. Here we present a solid-state system that integrates a trapped, electrically-controlled quantum system with near unity coupling efficiency to an external optical mode.

To achieve an efficient coupling, the quantum system must be placed in a high-quality microcavity so that it dominantly interacts with a single optical mode. Furthermore, this cavity mode must be mode-matched to an external mode to ensure efficient operation at the single photon level. The ideal operating point for such hybrid schemes is deep in the weak coupling (Purcell) regime of cavity quantum electrodynamics (QED), just below the onset of strong coupling. In addition, for cluster-state and distributed quantum computation, the hybrid system must be scalable. Our system satisfies these requirements in the solid-state. It is composed of self-assembled quantum dots (QDs) (density  $\approx 10\mu m^{-2}$ ) at the center of an oxidation-apertured micropillar cavity with integrated doped layers that enable an external bias to apply an electric field across the QD. This field causes carriers to tunnel in and out [13] of the QD, changing the QD charge state, and induces the quantum confined Stark effect [14, 15], shifting the emitted photon's energy. While cavity QED has been studied using quantum dots for several years, this has been done using a neutral exciton [16, 17]. Neutral excitons, bound electron-hole pairs, have been proposed as qubits [18] but seem problematic due to their quick spontaneous decay,  $\approx 1$  ns in GaAs, and fast dephasing [19]. The local qubit in our system is the spin of a trapped electron [20, 21], which interacts with

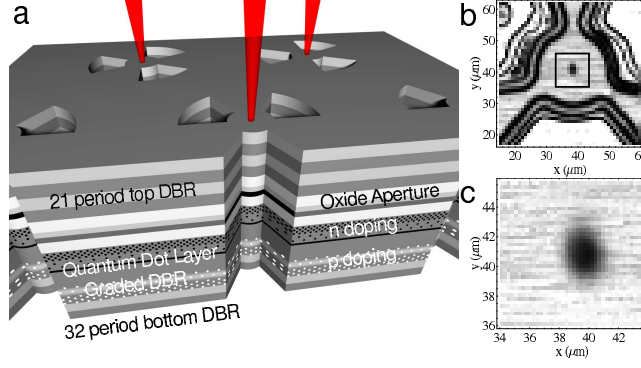


FIG. 1: (a) Schematic of the scalable solid-state cavity QED system based on electrically gated self-assembled QDs embedded in oxide-apertured micropillars. (b) Two-dimensional reflectivity scan of a micropillar cavity taken with a laser resonant with the cavity mode. The mode in the center can be seen clearly as a dip in the reflected signal. (c) Higher resolution reflectivity scan taken in a  $10\ \mu\text{m}$  by  $10\ \mu\text{m}$  area containing the mode, as depicted in (b).

the cavity mode through the addition of an exciton, forming a short-lived trion state. Since the polarization of the emitted photon is correlated with the spin state of the remaining electron, the trion acts as a readout channel of the spin [5]. Additionally, the micropillar cavity geometry is such that the fundamental mode is a doubly degenerate  $\text{HE}_{1,1}$  mode, which mode-matches well to external modes due to its Gaussian-like shape [22]. Here, we report on two variations of the solid-state cavity QED system, one optimized to operate in the charge-tuning regime, and the other in the Stark-tuning regime.

The demonstration of an electrically-gated QD embedded at the anti-node of a high  $Q$  cavity mode has become feasible through a series of scientific advances. Firstly, the development of vertical-cavity surface-emitting lasers (VCSELs) with oxide apertures in the GaAs/AlGaAs material system enabled the creation of cavities with small mode volumes,  $V_{eff} = 35(\lambda/n)^3$ , while maintaining a very high  $Q$  [23]. Secondly, the addition of single, self-assembled InAs/GaAs QDs embedded at the axial anti-node of the cavity mode provided an atomic-like emitter to couple to the optical mode [24]. Thirdly, the use of etched trenches to define the oxidation front, as shown in Fig. 1, enabled both control over the polarization degeneracy of the cavity modes as well as global electrical connection to an array of solid-state cavity QED systems [25]. In the experiments presented here, the oxidation time of the aperture is such to maximize the quality-factor,  $Q$ , while minimizing the mode volume. As

shown in Fig. 1b,c, the cavity mode is to a good approximation Gaussian in lateral profile and fits to a waist of  $2.2\ \mu\text{m}$ , in agreement with measurements of the spacing between different lateral modes [24].

Using a voltage source to create an electric field which properly drops over the QD active region is complicated by the presence of nearby material interfaces at each distributed Bragg reflector (DBR) period and at the oxide aperture region. These interfaces trap charges and result in the formation of charge domains, which reduce the field dropped across the QD region and hence obstruct controlled charging and Stark tuning [25]. To overcome these problems, a novel P-I-N device structure was developed in which the intrinsic region does not include the oxide aperture and the nearby p-doped  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$  DBR period is Al-content graded to and from the adjacent GaAs layers as shown in Fig. 1a. The Al-content grading prevents the formation of triangular potential wells that arise at abrupt  $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{GaAs}$  interfaces. Furthermore, all doping concentrations are graded such that the doped regions are easily contacted by countersink etching without introducing unnecessary dopants near the QD region. The two variations of the solid-state cavity QED system presented here have nominally the same growth structure, but the average doping levels for the charge tuning system are  $3.5\ 10^{18}\ \text{cm}^{-3}$  ( $2.5\ 10^{18}\ \text{cm}^{-3}$ ) for the n-doped (p-doped) layer whereas for the Stark tuning system they are  $7.0\ 10^{17}\ \text{cm}^{-3}$  ( $7.5\ 10^{17}\ \text{cm}^{-3}$ ).

To investigate the intra-cavity charging, we first characterized QDs outside of the cavities in the surrounding mirror region, where the Purcell effect is negligible. We monitored the photoluminescence spectrum (using a 1.25 m monochromator coupled with a CCD array) under 150 fs, 860 nm Ti:Sa laser excitation with 50 nW average power as the applied bias is varied. A typical trace for a single QD is shown in Fig. 2a. Near 18 V applied bias, there is a transition for the QD emission line to a line that is 6 meV to lower energy. This is the characteristic energy separation for the transition between the neutral exciton,  $X^0$ , and the singly electron-charged exciton,  $X^-$  [13, 26]. To verify the charge designations as  $X^0$  and  $X^-$ , we also measured the time-resolved decay of the photoluminescence using an avalanche photodiode with a time-to-amplitude converter. The result is shown in Fig. 2b, with curves taken at biases below (above) 18 V labelled as dashed (straight). Because of the presence of optically dark states, the  $X^0$  decay traces have a distinctive bi-exponential behavior, whereas the  $X^-$  decay are single exponentials [25, 27].

The same lifetime measurement is performed for QDs in the cavity region which are on

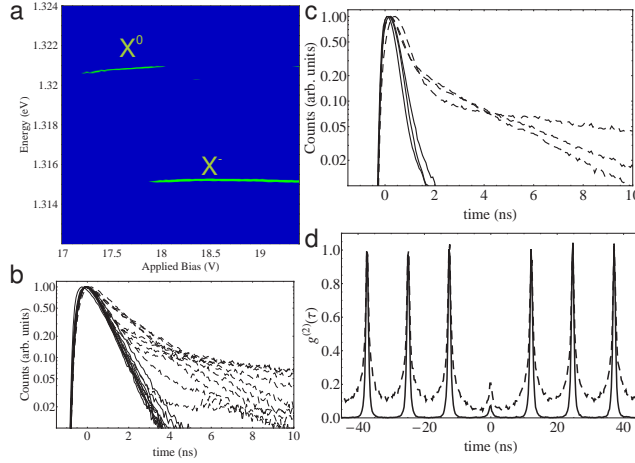


FIG. 2: (a) Photoluminescence spectra as a function of applied bias for a QD in the mirror region at 4 K. (b) Emission decay traces for 10 QDs in the mirror region. Straight traces are taken with 18.5 V applied bias ( $X^-$ ) and dashed traces are taken with 17.5 V applied bias ( $X^0$ ). (c) Emission decay traces for QDs on resonance with cavity modes for several different cavities. The straight (dashed) traces correspond to an  $X^-$  ( $X^0$ ) decay. (d)  $g^{(2)}(\tau)$  measurements for an  $X^-$  (straight) and  $X^0$  (dashed) transition.

resonance with a polarization-degenerate fundamental mode as shown in Fig. 2c (this was possible for approximately 10% of cavities), and the results qualitatively replicate that of the bulk QDs. However, the effect of the high  $Q$  cavity strongly reduces the emission lifetime by the Purcell effect. For some  $X^-$  cases, this lifetime approaches the timing resolution of our experiment, which is  $\sim 150$  ps and is due to the APD timing jitter. Nonetheless, a deconvolved lifetime of  $137 \pm 21$  ps was obtained for the fastest  $X^-$  transition and  $321 \pm 15$  ps for the  $X^0$ . This yields a Purcell enhancement,  $F_p = \tau_o / \tau_{cav}$ , of approximately 7 for the  $X^-$ . We measure that on average ( $F_p = 2.8 \pm 0.22$  for 4  $X^0$  transitions and  $5.9 \pm 0.96$  for 6  $X^-$ ) the Purcell enhancement is stronger for  $X^-$  than for  $X^0$ . Because both transitions have similar lifetimes in the DBR region, resulting from similar oscillator strengths, one would expect both to have similar Purcell effects. However, this is not found experimentally and may be due to a better matching of the transition dipole moment to the cavity mode polarization for the  $X^-$ . This could be explained by theoretical calculations beyond the standard techniques for calculating the optical transitions of a QD [28]. In addition, the second-order photon correlation function,  $g^{(2)}(\tau)$ , was measured as shown in Fig. 2d for

an  $X^0$  and an  $X^-$  transition. While both clearly demonstrate single photon behavior, the  $X^-$  is much cleaner due to its fast, single exponential decay. The measured single photon ( $g^{(2)}(0) < 0.25$ ) count rate was typically  $3 \times 10^6 \text{ s}^{-1}$  for an  $X^-$  with an 80 MHz pump rate, yielding a 25% extraction efficiency for the QD when corrected for the optical and detection losses of the setup, which correspond to a net efficiency of 15%.

While the lifetime measurements indicate that the emission is coupled to the cavity mode, it does not yield a quantitative measure of the coupling strength,  $g$ , or the mode-matching efficiency. To do this, one must probe the coupled system coherently and we accomplish this by measuring the reflectivity of the cavity-QD system [16, 17]. The reflection spectrum can be derived from the Jaynes-Cummings Hamiltonian using the input-output formalism and under sufficiently weak probing of a symmetric cavity [29, 30, 31, 32], can be expressed as

$$R(\omega) = \left| 1 - \frac{\kappa[\gamma - i(\omega - \omega_{QD})]}{[\gamma - i(\omega - \omega_{QD})][\kappa - i(\omega - \omega_c)] + g^2} \right|^2, \quad (1)$$

where  $g$  is the emitter-cavity coupling,  $\omega_{QD}$  ( $\omega_c$ ) is the emitter (cavity) resonance,  $\gamma$  is the dipole decay rate, and  $\kappa$  is cavity field decay rate. If there are no QDs coupled to the cavity mode, the spectrum shows a single dip at the cavity resonance with a width equal to the cavity field decay rate,  $\kappa$ , as shown in Fig. 3a. For this micropillar, we can fit the data to obtain  $\kappa = 24.1 \text{ } \mu\text{eV}$ , which corresponds to  $Q = 27,000$ . The depth of this dip is a measure of how well the probe beam is mode-matched to the cavity, and in this case the coupling efficiency is greater than 96%. This remarkably high efficiency implies that reliable information transfer at the single photon level is feasible and would constitute an increase in the success probability of a two-photon experiment [11, 12] by 3-4 orders of magnitude. If a QD is coupled to the microcavity, the reflection spectrum is drastically altered. Figure 3b shows the absolute reflection spectrum of the cavity mode interacting with a single QD transition. By fitting this spectrum to Eqn. 1, we obtain an emitter-cavity coupling of  $g = 9.7 \text{ } \mu\text{eV}$  and an emitter decay rate of  $\gamma = 1.9 \text{ } \mu\text{eV}$ . Since  $g/\kappa = 0.402$ , the emitter-cavity system is deep in the Purcell (weak-coupling) regime and at the precipice of the strong-coupling regime,  $g/\kappa > 0.5$ , exactly in the region ideally suited for hybrid quantum information schemes [5, 6, 8, 9]. The spectrum, with resolution limited by the probe laser linewidth, completely characterizes the system. Additionally, it reveals the natural linewidth of the QD transition with a signal much greater than achieved in transmission or differential transmission. In conclusion, the combination of these results for the cavity QED system

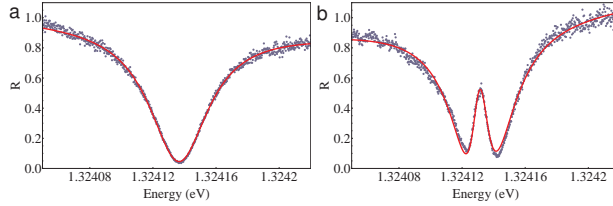


FIG. 3: (a) Cavity reflection spectrum of an unloaded micropillar cavity measured by recording the reflected signal of a tunable-wavelength laser. Eqn. 1 with  $g = 0$  plus a linear background is used to fit the data. (b) Cavity reflection spectrum of a QD coupled to the micropillar cavity in (a). Eqn. 1 plus a linear background is used to fit the data.

in the charge-tuning regime demonstrates that it is ideal for hybrid quantum information processing.

We now turn to the Stark-tuning cavity QED system. Since the coupling between the QD and the cavity mode depends on the spectral detuning, an external control is necessary to reach resonance. In QD systems without electrical gating, this control is achieved by adjusting the sample temperature [17]. However, this control typically decreases coherence within the system through higher phonon occupations and is not scalable. An applied electric field can also tune the QD transition via the Stark Effect without the negative effects of temperature and in principle can be scalable by gating each cavity separately. In order to illustrate this effect and potential applications, we utilized a polarization non-degenerate cavity mode. As mentioned in Ref. [25], an engineered ellipticity of the aperture lifts the polarization degeneracy, creating two orthogonal linear polarization modes (denoted as H and V) as illustrated in Figure 4a. Because the  $Q$  factor is very high (40,000), the modes can be spectrally separated by as little as  $50 \mu\text{eV}$  and still be resolved. This enables the quantum dot transition to be Stark-shift tuned into resonance with two modes as shown in Fig. 4b. Note that the dependence is nonlinear with bias as expected for the Quantum Confined Stark Effect [14, 15].

By Stark-shift tuning the QD emission, a polarization-dependant Purcell effect is observed on resonance with each mode. Stark shift tuning as opposed to current induced heating was confirmed by observing a constant QD linewidth over the tuning range. For several applied biases, the QD emission decay curve is measured, see Fig. 4c, and the extracted lifetime is plotted as a function of spectral position as shown in Fig. 4d. The dips in the

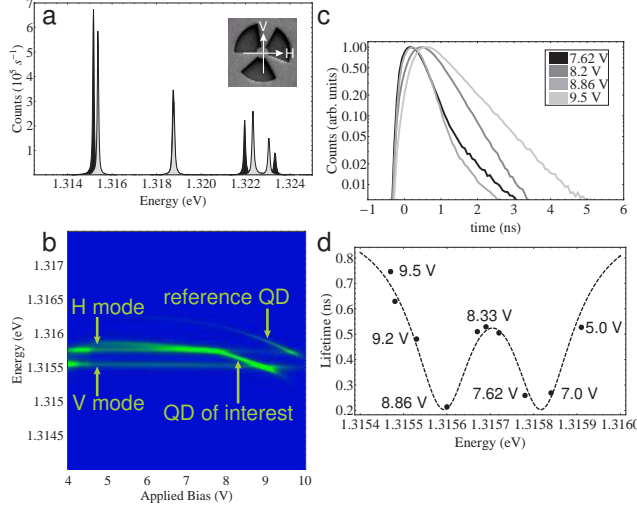


FIG. 4: (a) Micro-photoluminescence spectra of non-degenerate optical modes in a micropillar. H (V) polarized modes are black (grey). Inset: SEM image of a micropillar. (b) Photoluminescence spectra as a function of applied bias for two QDs (labeled QD of interest and Reference QD) and two nondegenerate fundamental cavity modes (labeled H mode and V mode). (c) Lifetime traces for a few bias settings; 7.62 V, 8.2 V, 8.86 V, 9.5 V. (d) Deconvolved lifetimes as a function of emission energy with fit.

transition lifetimes measured on resonance are a clear consequence of the Purcell effect. The lifetimes at the resonance of each mode is measured to be around 220 ps as shown in Fig. 4d, approximately 5 times shorter than the bulk lifetime. The appearance of a bi-exponential, most prevalent for the on resonance biases, in Fig. 4c is attributed to a small fraction ( $\sim 4\%$ ) of photons collected from QDs outside the mode volume. Stark-shift tuning when used in addition to charge tuning constitutes a completely bias-controlled, solid-state cavity QED system.

In conclusion, we presented a solid-state cavity QED system which has near ideal properties for photon electron-spin coupling as needed for hybrid quantum information processing. The unique features of our system are intra-cavity electron charging, near perfect mode-matching, polarization control of the cavity modes, and operation deep in the Purcell regime. In addition, the cavity-QD coupling can be controlled via the Stark Effect, which has applications for quantum and classical communication. The combination of this work with spin initialization, manipulation, and readout [26, 33, 34, 35] as well as techniques for

active positioning of quantum dots [36] will bring the implementation of solid-state hybrid quantum information protocols within reach.

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